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Geothermal Power for Integration of Intermittent Generation

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Abstract

State renewable portfolio standards requiring more intermittent wind and solar generation will substantially increase the uncertainty and variability in grid operations. Geothermal power plant operators could mitigate variability and uncertainty by operating plants in a more flexible mode. This study explores economic incentives and innovative reservoir management for geothermal plant operators to provide such flexibility.

1.0 Introduction

Many states are adopting renewable portfolio standards that require procurement of wind, solar, and other intermittent renewable generators to meet goals within a given timeframe. For example, California is requiring 33 percent renewable energy generation by the year 2020 (State of California, 2011). Increased contributions from intermittent generators will substantially increase the variability and uncertainty in generation resources available to grid operators. Accordingly, the California Independent System Operator (CAISO) and others have undertaken several studies to estimate the impacts of this increase in variability and uncertainty (CAISO, 2010; Rothleder, 2011).

An example of these impacts in California is shown in **Figure 1.1** (Liu, 2012). The figure shows gross load, solar generation, wind generation, and the resulting net load when wind and solar generation are subtracted from the gross load during a low-load spring day in the year 2020. As indicated in the figure, very high ramp rates are observed in net load. Although wind generation is fairly constant on this particular day, in general it can be highly variable and uncertain.

Independent system operators must manage this increase in variability and uncertainty with flexible and dispatchable generation, storage, and demand response resources. This study conducts a system level economic analysis to quantify additional revenue streams that geothermal energy systems could receive by providing operational flexibility to independent system operators in the western U.S. Geothermal power system design modifications and changes in operating policies are analyzed using historical price data for the years 2011–2013 and results from a prospective integrated weather, renewable generation, and production simulation model of the year 2020. In particular, the value of providing ancillary services (frequency regulation services at sub-second time intervals, load following services at five-minute time intervals, spinning reserve, and non-spinning reserve) are examined. Parametric studies of geothermal system design parameters and operating policies are conducted to help identify optimal courses of action.

2.0 Energy and Ancillary Service Prices

This section covers historical and future prices of energy and ancillary services. There are four types of ancillary service products: regulation up, regulation down, spinning reserve, and non-spinning reserve. Regulation is used to control system frequency that can vary as generators access the system and must be maintained very narrowly around 60 hertz. Units and system resources providing regulation are certified by the ISO and must respond to “automatic generation control” (AGC) signals to increase or decrease their operating levels depending upon the service being provided, regulation up or regulation down. Spinning reserve is the portion of unloaded capacity from units already connected or synchronized to the grid and that

can deliver their energy in 10 minutes. Non-spinning reserve is capacity that can be synchronized and ramped to a specified load within 10 minutes.

2.1 Historical Prices

Historical and prospective price patterns are used to evaluate the revenue potential of providing ancillary services, and the opportunity costs of reductions in energy deliveries required to permit delivery of ancillary services. Historical prices are obtained from the California Independent System Operator OASIS database (OASIS, 2014).

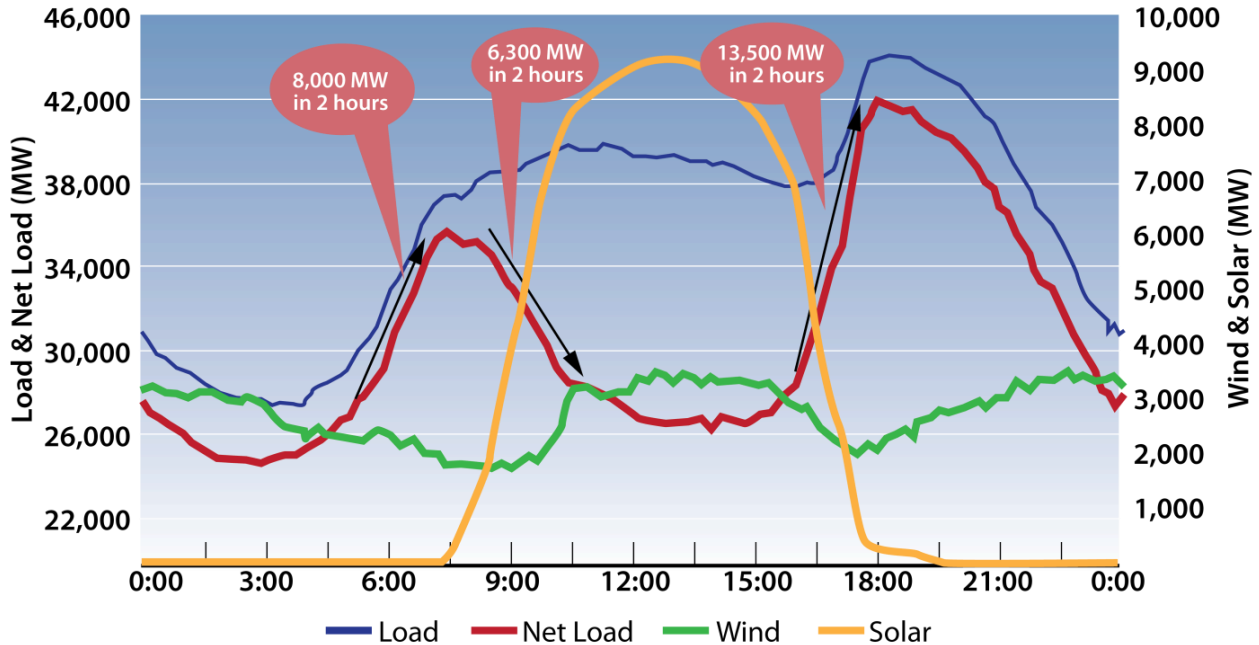


Figure 1.1. Projected gross load, renewable generation, and net load in California in 2020.

Marginal hourly energy prices for each hour in the year 2013 are shown in **Figure 2.1**. Horizontal lines in the figure correspond to days of the year and vertical lines correspond to hours of the day. Marginal hourly energy prices in \$/MWh in southeastern California are color coded according to the scale at the right. Note that peak prices of \$180/MWh occur during a few hours of the summer peak. Peak prices during other times of the year are \$60-80/MWh in the mornings and evenings. Off peak prices are less than \$40/MWh. One exception to this pattern is a period of several days in November when prices are in the \$60-80/MWh range throughout the day.

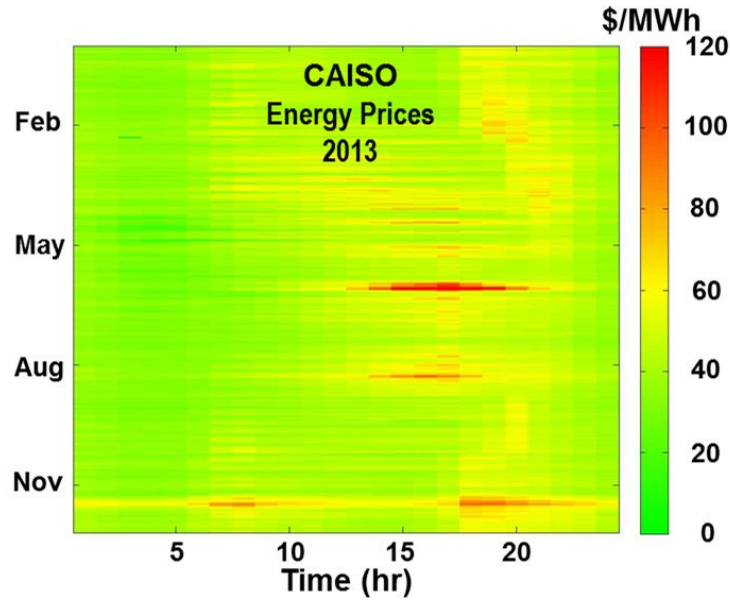


Figure 2.1. CAISO energy prices (\$/MWh) in 2013.

Prices for the frequency regulation up ancillary service in each hour of the year 2013 are shown in **Figure 2.2a**. As indicated in the figure, prices of approximately \$100/MW were observed during summer peak loads in August. As was the case with energy prices, slightly higher (lighter green) prices are observed during the morning and evening peaks. Prices for frequency regulation down are shown in **Figure 2.2b**. Prices of approximately \$20/MW (yellow) were observed in the early morning from late April to May. Prices during other hours in the year are in the range of \$5-10/MW. Although not very apparent in **Figure 2.2b**, low regulation-down prices occur after the August afternoon peak load (**Figure 2.1**). Prices during other hours in the year are in the range of \$0-20/MW.

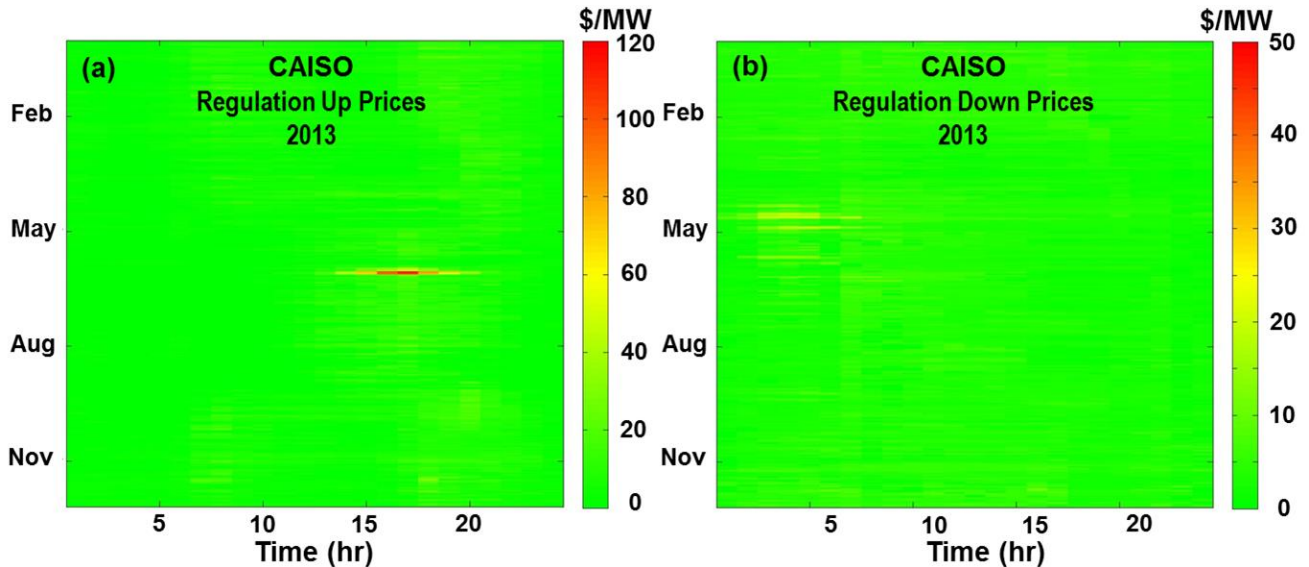


Figure 2.2. CAISO prices (\$/MW) in 2013 for (a) regulation up and (b) regulation down. Note the different color scales.

Prices for spinning reserve are shown in **Figure 2.3a**. As indicated in the figure, prices of approximately \$100/MW were observed during summer peak loads in June–July. Prices during other hours in the year are in the range of \$0-30/MW. Prices for non-spinning reserve are shown in **Figure 2.3b**. Price patterns are similar to the spinning reserve prices, although the duration of the high price periods observed during the

summer peaks are shorter. Energy and ancillary service prices at CAISO for the years 2011 and 2012 are shown in **Appendix A**. A general increasing trend in prices can be observed over this three-year period.

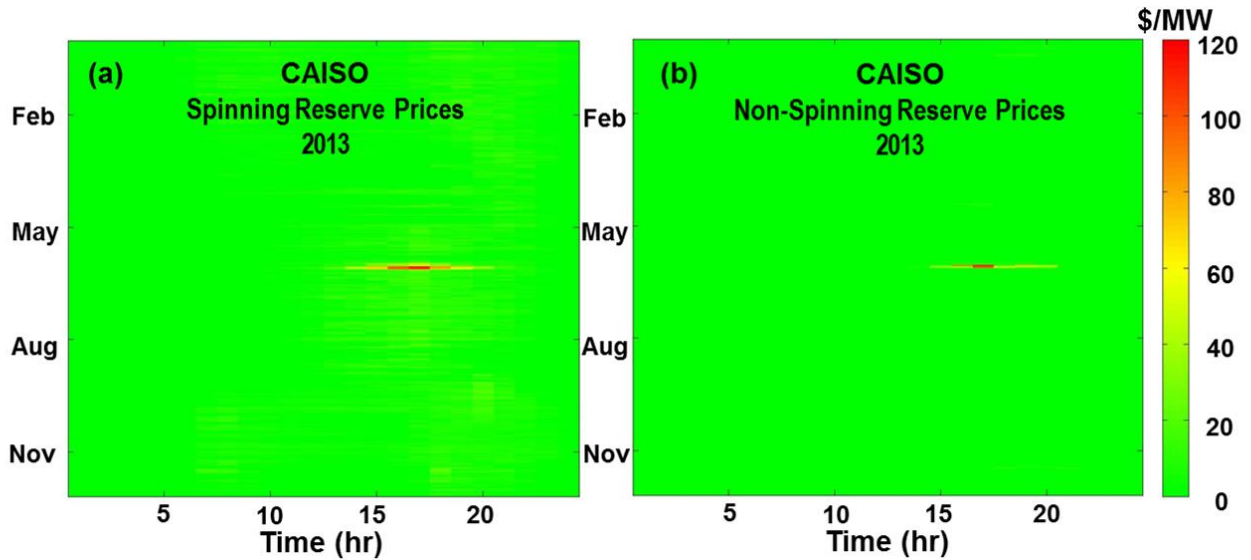


Figure 2.3. CAISO prices (\$/MW) in 2013 for (a) spinning reserve and (b) non-spinning reserve.

2.2 Short-term price spikes in 2013

The prices shown in the previous figures are *hourly* average prices. Shorter-term price spikes up to \$1,000/MWh have been observed in the major markets in 2013. These price spikes typically last for five or ten minutes. Some examples are shown in **Figure 2.4** (LCG Consulting, 2014).

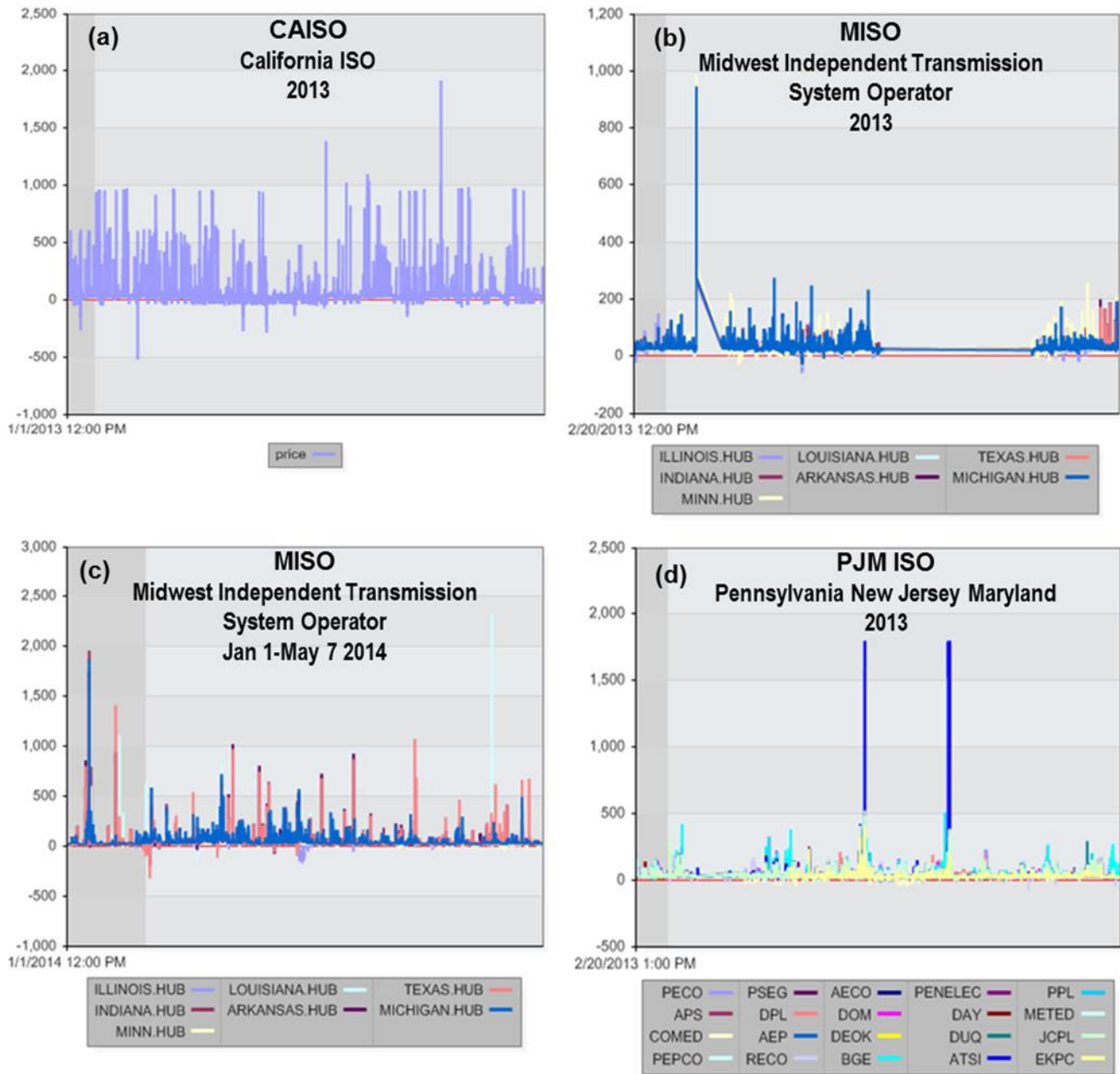


Figure 2.4. Energy prices (\$/MWh) in (a) California ISO market in 2013, (b) Midwest ISO market in 2013, (c) Midwest ISO market from Jan. 1–May 7, 2014, and (d) PJM ISO market in 2013 (LCG Consulting, 2014).

Energy prices in the California ISO market for the year 2013 are shown in **Figure 2.4a**. As indicated by the data in the figure, Prices exceed \$500/MWh approximately sixty times during 2013. The price is \$2,000/MWh during one period in September. Prices are less than -\$100/MWh during six periods, when over-generation conditions are experienced. Similar patterns can be observed for the first four months of 2014.

In general, prices in other markets were less volatile than California prices during 2013—positive price spikes were less frequent and few negative price spikes were observed. This may be due to more efficient market implementation, more aggressive demand response programs, or less intermittent renewable generation in these other markets.

Energy prices in the Midwest ISO market for the year 2013 are shown in **Figure 2.4b**. Except for one \$900/MWh price spike in February, prices are less than \$300/MWh. There is a period of missing data in the source's database. The prices during the first four months of 2014 shown in **Figure 2.4c** indicate higher volatility in the Midwest for the year 2014.

Energy prices in the Pennsylvania-New Jersey-Maryland (PJM) market are shown in **Figure 2.4d**. As indicated by the data in the figure, prices reach \$1800/MWh twice during 2013. There appear to be more price spikes in the Baltimore Gas and Electric (BGE) service territory than the other utilities. Prices in the PJM market are rarely negative.

2.3 Prices in 2020

As discussed previously, California's 33 percent renewable energy goal by 2020 is expected to increase ancillary service prices in that year. LLNL has completed a study of energy markets in the Western U.S., including forecasts of energy and ancillary service prices (Edmunds et al., 2013).

Forecasts of marginal energy prices in California are shown in **Figure 2.5**. As indicated by the data in the figure, prices exceed \$100/MWh during the evening peak load. Higher prices are also observed during a morning peak.

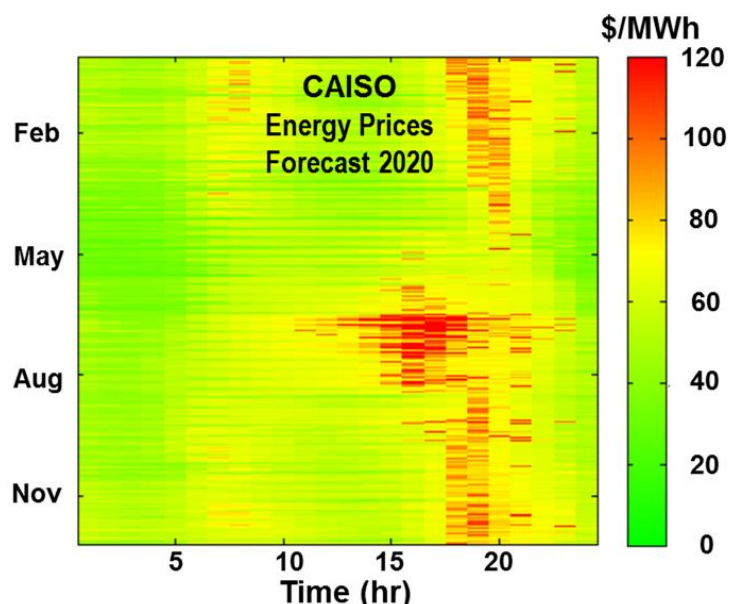


Figure 2.5. Energy price forecast for the California ISO market in 2020 (\$/MWh).

The California ISO is in the process of defining flexibility products to provide load following capabilities to be traded in the market. These load-following products require flexibility of dispatch in the real-time market. For the LLNL study, it was assumed that dispatch would occur at five-minute intervals in the year 2020. The prices for load following up ancillary services are shown in **Figure 2.6a**. Price patterns for this ancillary service generally coincide with energy price patterns. Prices for load following down ancillary services are shown in **Figure 2.6b**. Load following down prices are high late at night and early in the morning when load is falling to a daily minimum. Load following down prices are also high just before noon in the winter, spring, and fall. This is due to a combination of low gross load and high solar generation rates which decrease the net load during this time period. Over-generation conditions may sometimes exist.

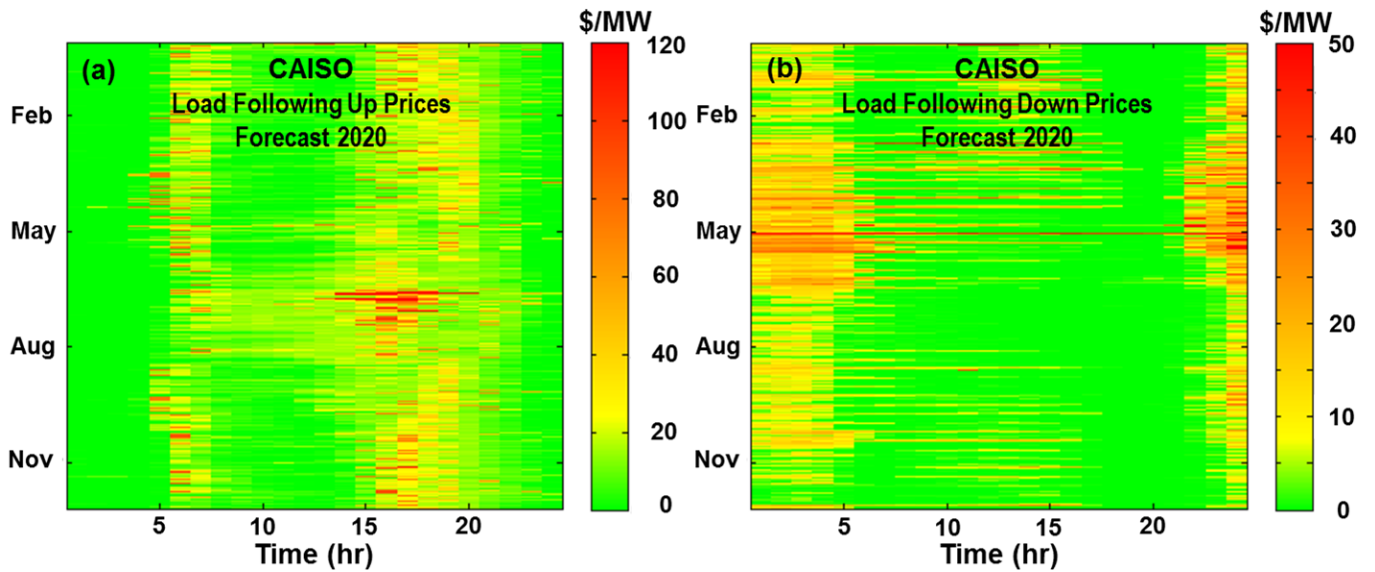


Figure 2.6. Ancillary service price (\$/MW) forecast for the California ISO market in 2020 for (a) load following up and (b) load following down. Note the different color scales.

Frequency regulation up and regulation down ancillary service prices are shown in **Figures 2.7a** and **2.7b**, respectively. The regulation-up price patterns generally mirror energy and load following up prices. Regulation-down prices are high late at night and early in the morning when load is falling to a daily minimum. Different color scales are used in **Figure 2.7** because regulation-down prices are generally less than half of the regulation-up prices.

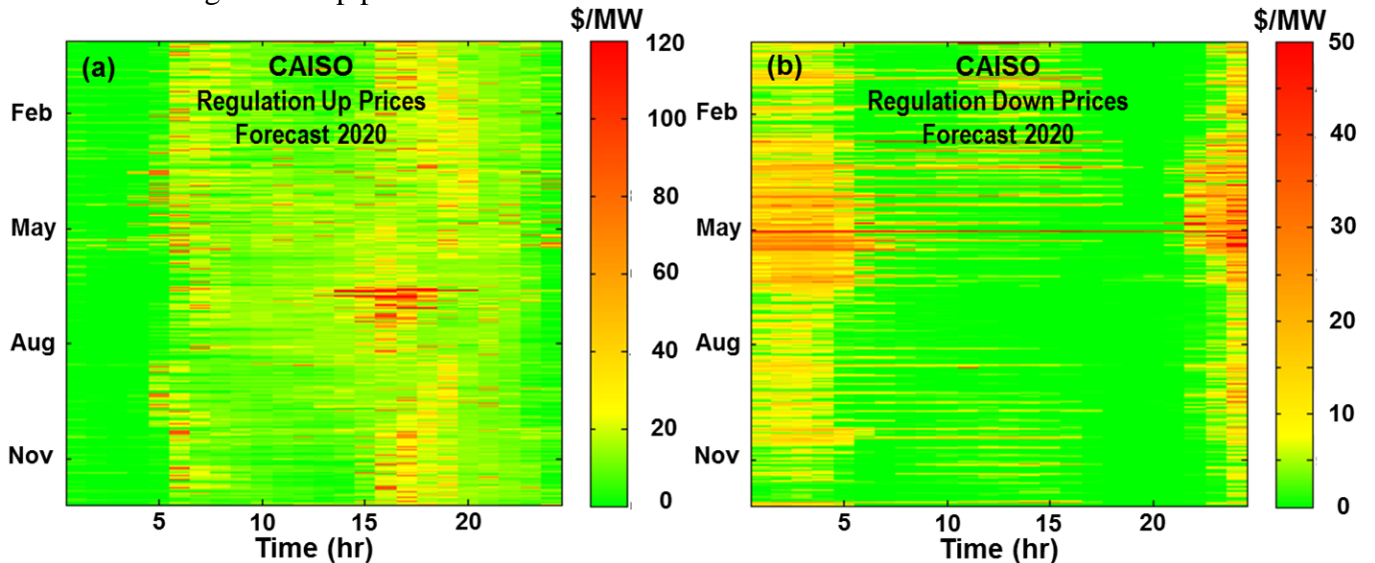


Figure 2.7. Ancillary service price (\$/MW) forecast for the California ISO market in 2020 for (a) regulation up and (b) regulation down. Note the different color scales.

Finally, hourly prices for spinning and non-spinning ancillary services are shown in **Figures 2.8a** and **2.8b**, respectively. Spinning reserve services provide significantly more revenue potential than non-spinning reserve.

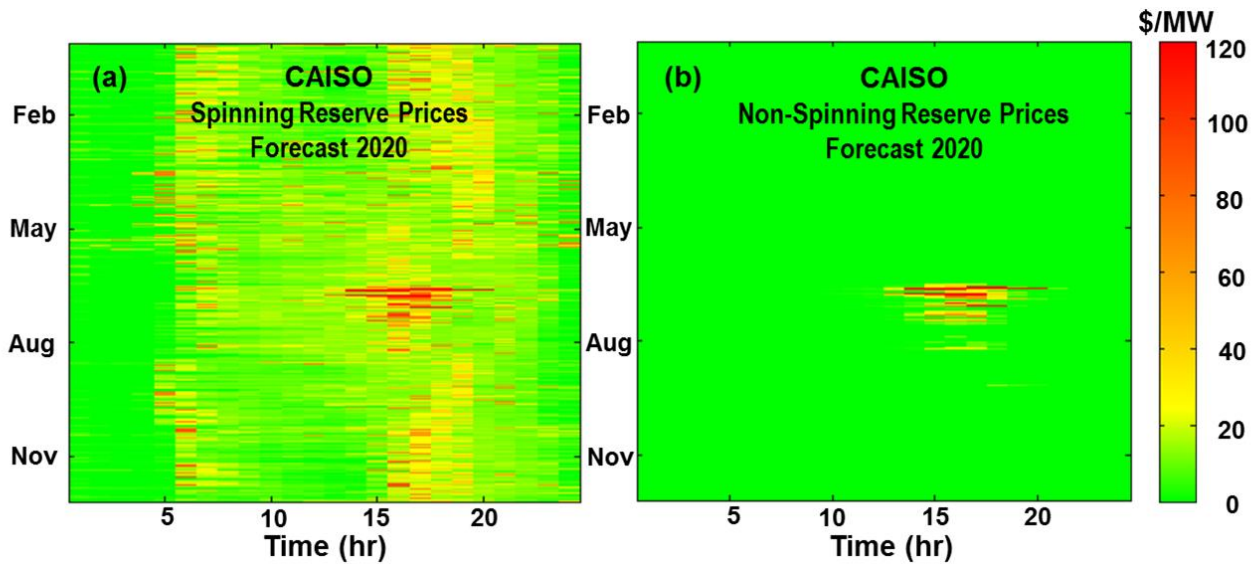


Figure 2.8. Ancillary service price (\$/MW) forecast for the California ISO market in 2020 for (a) spinning reserve and (b) non-spinning reserve.

3.0 Business Models for Geothermal Projects

From an engineering perspective, geothermal projects are technically capable of providing a range of ancillary services. For example, Ormat Corporation’s 38 MW Puna geothermal plant in Hawaii provides 8 MW of capacity that is controlled by Hawaii Electric Company. The plant provides regulation and ramping services to the utility (AltEnergy, 2014). Geothermal plants could capture some of the ancillary service revenues described previously.

However, the economic incentives associated with the sale of ancillary services may not warrant deviation from an operating strategy of producing as much energy as possible. Due to high energy prices negotiated in recent geothermal power purchase agreements (PPAs), a reduction in energy generation needed to support provision of ancillary services (AS) will incur an economic penalty if AS prices are below energy prices. For example, Ormat recently executed a contract with the Southern California Public Power Authority to provide energy at \$99/MWh from its 16 MW Don A. Campbell geothermal plant in Nevada (Energy Business Review, 2014). Revenues from the contract are driven solely by the number of MWh delivered. Other contracts include¹:

- Cyrg Energy plant in New Mexico at \$98/MWh with a 2.75 percent per year price escalation over 20 years
- Trans Alta-Mid American Energy plant in Riverside, California at \$70/MWh with a 1.5 percent price escalation over 24 years
- U.S. Geothermal plant in Nevada at \$90/MWh with a 1 percent price escalation rate over 25 years

If contracts were written to provide some measure of flexibility with regard to the services they are providing (energy vs. ancillary services), a plant operator could shift from one contractual mode to another. The plant could provide regulation, load following, spinning, or non-spinning reserve ancillary services in those hours in which the price of the ancillary services exceeded the contractual energy price. However, at the energy prices in these recently-executed PPAs, there are few hours in the year when ancillary service prices exceed these energy prices. The short-duration price spikes in 2013 described in Subsection 2.2 are not frequent enough and of sufficient duration to provide enough incentive to deviate from an energy-only PPA at high

¹ <http://www.utilitydive.com/news/the-forgotten-renewable-a-users-guide-to-geothermal/218374/>

energy prices. Accordingly, there would be few hours in the year when geothermal operators would be willing to reduce energy deliveries in order to provide ancillary services. Geothermal power generators would have more incentive to provide ancillary services if PPAs included a capacity payment and a lower energy price. Under such PPA structures, there would be more hours in the year when AS prices would exceed energy prices and operators would be willing to switch and deliver AS products. Industry, state energy policy staffs, and other stakeholders should consider promoting such contract structures in the future.

In addition, some ancillary service markets may not be sufficiently large to impact the overall economics of the geothermal industry. Only a few hundred MW of capacity are needed for regulation services in the California ISO. The size of the market for load following ancillary services in California has yet to be determined because this product is currently under development by CAISO.

Finally, other potential revenue streams could be exploited. For example, revenue could be derived from extracting lithium and other minerals from the brine stream. Simbol Corporation has demonstrated at the pilot scale a new technology for extracting lithium from hot brine and is preparing to break ground for a production scale plant in August 2014 (The New York Times, 2014). The plant will be capable of producing 15,000 metric tons of lithium carbonate annually. At current lithium prices of \$6,500 per ton lithium carbonate, this represents a revenue stream of approximately \$100 million per year. This lithium revenue stream would be derived from the brine stream from a 60 MW geothermal power plant. Hence, for an integrated geothermal power and lithium carbonate production facility, lithium production could add an additional \$200/MWh of revenue to the price the power plant charged for energy².

4.0 Geothermal Reservoir Management

4.1 Background on Reservoir Management

Geothermal reservoir management can compensate for imbalances between load and available generation on the grid. There are two fundamental ways in which geothermal resources can provide this service:

1. The *gross* power output from a geothermal power plant can be adjusted to match the variable supply from other grid resources with the actual demand by scheduling the timing and magnitude of energy withdrawal from the reservoir. This ‘supply-response matching’ approach may be applied to all types of geothermal power systems.
2. A portion of the parasitic load associated with power generation can be time-shifted to adjust the *net* power output. This ‘time-shifting’ approach depends on reservoir conditions and how heat is recovered from the reservoir; it can be particularly useful for overpressured reservoirs that do not require submersible pumps for heat recovery. The multi-fluid geothermal energy system approach, designed to create an overpressured reservoir, can stabilize electricity grids and provide bulk energy storage (BES) by using cyclic-injection/pressure-augmentation, rather than steady-injection/pressure-augmentation to drive fluid recirculation.

The first approach does not use the full capacity of the geothermal power plant (and the associated capital investment), and thus increases the levelized cost of electricity (LCOE). If variable heat withdrawal involves complete suspension of fluid/enthalpy production, it may also result in operational issues associated with exacerbated duty cycles from heating and cooling components of the power system. Conversely, variable/intermittent heat withdrawal delays the thermal decline of the reservoir, relative to the decline that would result from continuous withdrawal at full plant capacity. This delay would likely extend the useful lifetime of the geothermal power system and time-shift revenue to a later date, but this may decrease the net

² Assuming a 90% capacity factor for the geothermal plant, lithium production revenues would be $\$100,000,000 / (60 \text{ MW} * 8760 \text{ hr} * 0.9) = \$200/\text{MWh}$ of energy produced. Parasitic load associated with lithium production would decrease revenues from lithium generation.

present value of the project, and thus negatively impact the financial viability of the system. However, if variable heat withdrawal involves only the reduction of fluid/enthalpy production rates, rather than complete suspension, it can minimize temperature fluctuations of the power system components. Moreover, if variable heat withdrawal is conducted on a diurnal basis, it will allow for increased power output during periods of high electricity demand, which can improve financial viability of the system.

The second approach (parasitic-load time-shifting) uses the full capacity (and the associated capital investment) of most of the components of the power plant, including the turbines and the injection and production wells, which comprise the majority of the capital cost. As a consequence, the second approach will likely have a smaller LCOE than the first approach. The primary components that must be oversized, relative to the power plant capacity, are those associated with working-fluid reinjection into the reservoir. Because this approach generates revenues typically associated with geothermal power sales, as well as those associated with providing ancillary services and BES, it can further decrease the LCOE. Because the parasitic load can be scheduled to use the lowest-price electricity, the variable cost of electricity can be reduced. This approach allows the power turbines to spin continuously at full capacity, enabling faster response to grid imbalances. When most of the parasitic load is shifted to periods of low electricity demand, more power can be delivered to the grid when demand is high, because net power is nearly equal to gross power, which will increase revenues.

The second approach takes advantage of the fact that much of the parasitic load in geothermal power systems is associated with the power required to recirculate the working fluids for heat extraction, which is typically brine. For vapor-dominated reservoirs or liquid-dominated artesian reservoirs—which are naturally overpressured above hydrostatic pressure—most of the parasitic load is that associated with reinjecting condensate or brine, or with transporting and injecting *make-up* water from a separate source. For liquid-dominated hydrostatic reservoirs, most of the parasitic load is associated with lifting brine up the production wells. Submersible pumps, which typically provide this lift, can consume a large fraction of the electricity generated by the power plant, particularly for low-temperature resources. Because this parasitic load cannot be time-shifted, it is useful to find alternative means of driving fluid recirculation, as provided by the multi-fluid geothermal energy system approach (Buscheck 2014a; 2014b). For hydrostatic reservoirs, the parasitic load of brine reinjection is relatively small, and time-shifting this load may not be useful. Because the power requirements for reinjecting brine into overpressured reservoirs can be relatively large, time-shifting this parasitic load can be a useful means of providing ancillary services, as well as providing BES over days to weeks or longer.

4.2 Multi-Fluid Geothermal Energy Systems in Sedimentary Geothermal Resources

Sedimentary resources typically have lower temperatures and energy densities than hydrothermal resources, but they often have higher permeability and larger areal extents. Consequently, spacing between injection and production wells is likely to be wider in sedimentary resources, which can result in more fluid pressure loss, increasing the parasitic cost of powering the working fluid recirculation system, compared to hydrothermal systems. The multi-fluid geothermal energy approach is being developed to create overpressured reservoir conditions and to provide multiple, more efficient working fluids for pressure augmentation, energy storage, and energy withdrawal (Buscheck 2014a; 2014b; Buscheck et al., 2014; 2015). This approach involves injecting CO₂ that is captured from fossil-energy systems and/or N₂ that is separated from air (**Figure 4.1**). The hydraulic conditions in the subsurface reservoir are engineered by using concentric rings of horizontal injection and production wells that create a hydraulic divide to store pressure, CO₂, and N₂. The engineered system can be pressurized (recharged) when the power that is supplied to the grid exceeds the demand placed on the grid; the system is depressurized (discharged) when demand exceeds supply. Thus, this approach shares some of the attributes of pumped storage hydro (PSH) and its recently evolving subsurface equivalent, called underground pumped hydro storage (UPHS). Because of their compressibility, supercritical CO₂ and N₂ function as cushion gases to provide enormous storage capacity—similar to compressed air energy storage (CAES). Because the

ability to store energy increases with the ability to store pressure and because pressure-storage capacity increases linearly with the volume of cushion gas, BES capacity increases with stored CO_2 and N_2 mass.

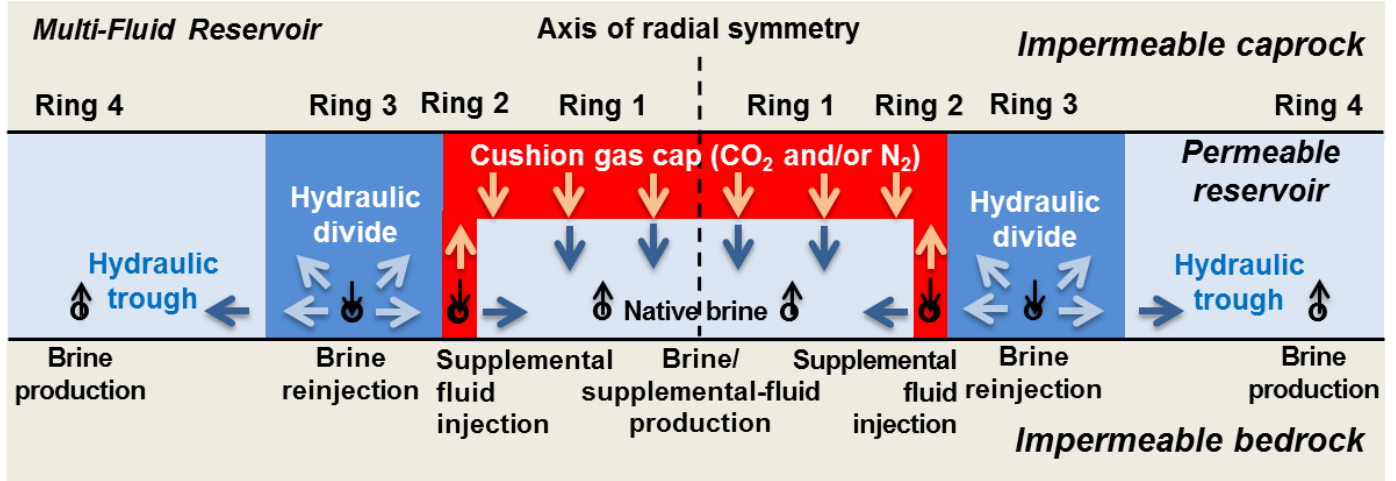


Figure 4.1. Multi-ring, horizontal-well configuration used in the multi-fluid geothermal energy system approach is shown (Buscheck, 2014a; 2014b). Due to buoyancy, supplemental fluid migrates to the top of the reservoir to form a “cushion gas” cap that increases the pressure-storage (and BES) capacity of the system.

Supercritical CO_2 and N_2 are also useful heat extraction fluids for efficient power conversion in CO_2/N_2 turbines. Injecting CO_2 and N_2 also displaces large quantities of brine that can serve as *make-up* fluid to reduce the water intensity of power generation. Some of this make-up brine can be used to cool the power plant, which can be particularly useful in water-constrained regions. Because it is readily available, N_2 can be separated from air, compressed, and injected whenever it is advantageous to do so. Unlike air used in CAES, N_2 is non-corrosive and will not react with the reservoir formation. Time-shifting the parasitic loads associated with pressurizing brine and N_2 can provide BES over days to months. Further, continuous modulation of the parasitic loads can provide ancillary services (e.g., load-following at five-minute intervals, response to automatic generator control signals at four-second intervals, and frequency regulation at sub-second intervals).

A recent study (Buscheck et al., 2014) considered a wide range of cases that provide BES using time-shifted N_2 separation, compression, and injection, including the following two examples (**Figure 4.2**):

1. **10/10 day cycle BES:** 10 days of 240-kg/sec N_2 injection, followed by 10 days of zero injection.
2. **3/9 month cycle BES:** 3 months of 480-kg/sec N_2 injection, followed by 9 months of zero injection.

For the 10/10 day cycle BES case, the influence of cyclic N_2 injection is hardly evident in the time series of brine production, net power, and N_2 injection-well overpressure (**Figure 4.2**). The breakdown of gross power, parasitic load, and net power are virtually the same for the no-BES case and corresponding BES case over the 30-year production period (**Table 4.1**). For the 3/9 month cycle BES case, the influence of cyclic N_2 injection is evident in the time series of brine production, net power, and N_2 injection-well overpressure. However, the breakdown of gross power, parasitic load, and net power are virtually the same (**Table 4.1**). The influence of cushion-gas volume is clearly evident, as doubling the volume of cushion gas (129 km^2 footprint), reduces the oscillations in overpressure, brine production and net power by a factor of two (64 km^2 footprint).

For these BES simulations, time-shifting the parasitic load of N_2 separation, compression, and injection never results in loss of geothermal power generation capacity. Thus, time-shifting this parasitic load is found to result in 100 percent round-trip efficiency, even for the 3/9 month cycle BES case. Time-shifting the parasitic load of N_2 injection results in BES rates ranging from 71.7 to 375.5 MW and in stored energy per cycle ranging from 18.1 to 333.9 GWh (**Table 4.1**).

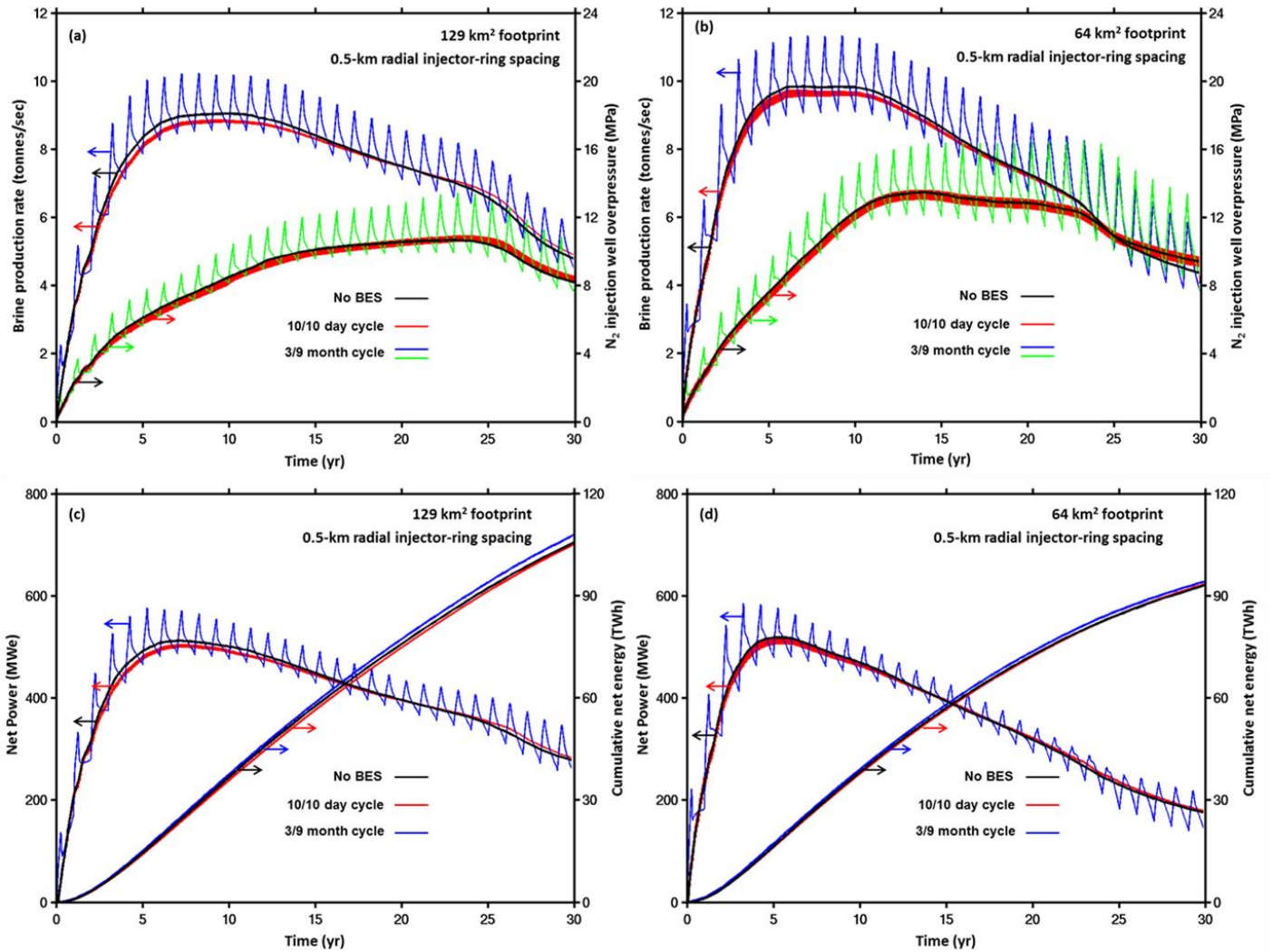


Figure 4.2. Time series of net power and overpressure, with and without BES, for well-field footprints of (a,c) 129 km² and (b,d) 64 km². The average N₂ injection rate is 120 kg/sec. The reservoir thickness is 250 m and depth is 5 km. Cases are plotted for (1) no BES, (2) 10/10 day cycle BES: 10 days of 240-kg/sec injection and (3) 3/9 month cycle BES: 3 months of 480-kg/sec injection (Buscheck et al., 2014).

Table 4.1. Power averaged over 30 years using time-shifted N₂ parasitic load (Buscheck et al., 2014).

Production footprint area (km ²)	Energy storage cycle injection/no injection	Energy storage rate (MW)	Energy stored per cycle (GWh)	Power (MW)		Parasitic load (%)		
				Gross	Net	N ₂ pumping	N ₂ separation	Brine pumping
129	No BES	NA	NA	551.9	402.3	1.9	4.9	20.3
	10/10 day cycle	75.3	18.1	548.5	400.2	2.0	4.9	20.2
	3/9 month cycle	152.4	333.9	569.0	411.3	1.9	4.8	21.2
64	No BES	NA	NA	543.8	354.4	2.1	4.6	28.2
	10/10 day cycle	71.7	17.2	541.8	355.7	2.1	4.5	27.7
	3/9 month cycle	148.4	325.2	564.2	358.5	2.0	4.6	29.9

While time-shifting the parasitic load to compress and inject N₂ was found to be useful for BES, recent studies of multi-fluid geothermal energy systems (Buscheck et al., 2014; 2015) show that the parasitic load of pressurizing and injecting brine comprises about 75 to 99 percent of the total parasitic load for fluid recirculation. Examples of time-shifting the brine parasitic load for the purpose of *diurnal* BES are compared to the corresponding cases of no BES in **Figure 4.3** and **Table 4.2**.

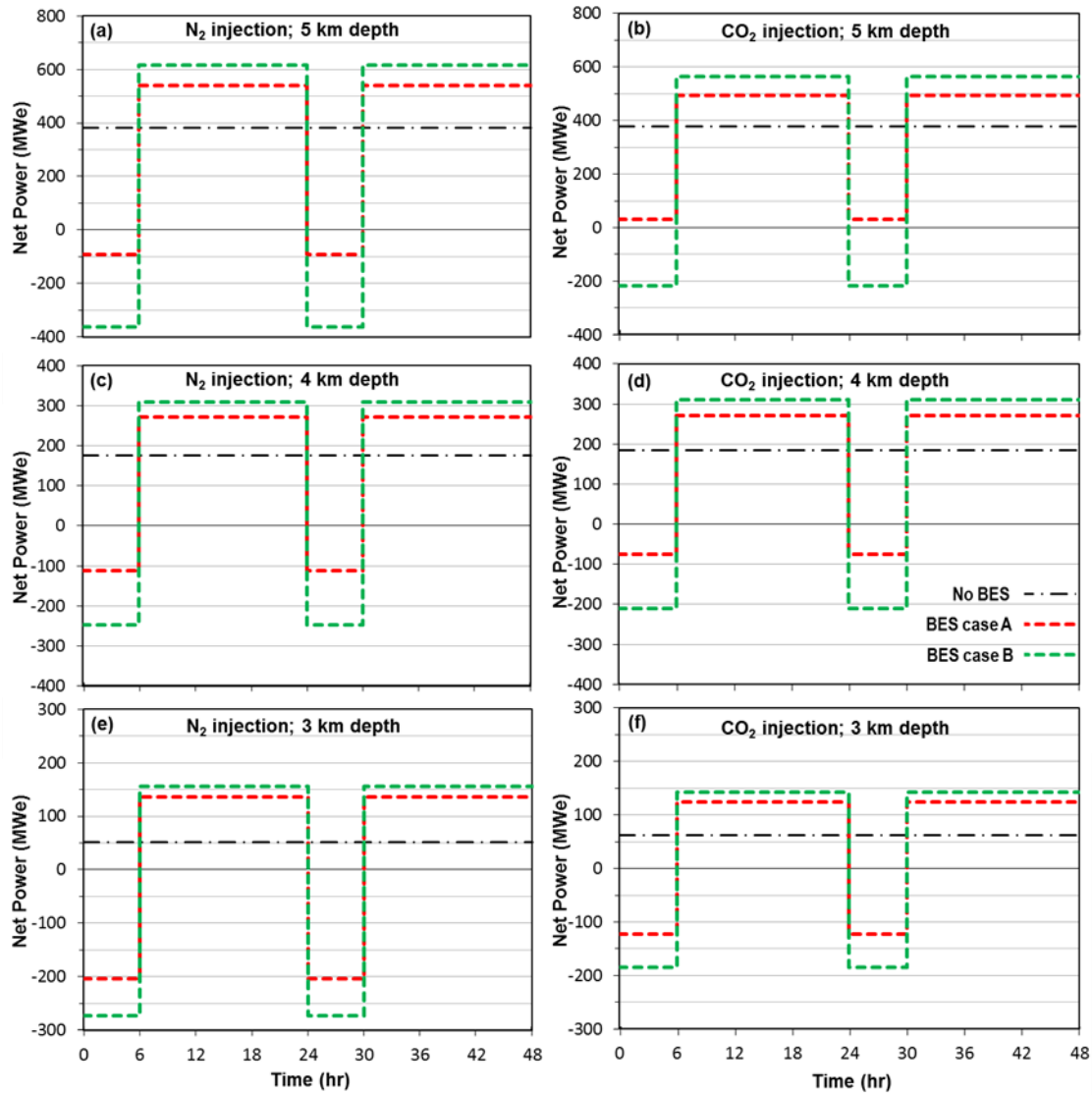


Figure 4.3. Time series of net power are plotted for a 48-hour period that occurs 10 years into production for initial and maximum N₂ or CO₂ injection rate of 120 and 240 kg/sec, respectively, reservoir thickness of 125 m and reservoir depths of 3, 4, and 5 km. Cases include (1) no BES, (2) diurnal BES case A: time-shift brine parasitic load to a 6-hour recharge period per day, and (3) diurnal BES case B: same as case A plus reduce fluid/enthalpy production during the 6-hour recharge period (Buscheck et al., 2015).

Table 4.2. The power performance at 10 years is summarized for cases with an initial N₂ or CO₂ injection rate of 120 kg/sec and a maximum N₂ or CO₂ injection rate of 240 kg/sec (Buscheck et al, 2015).

Depth (km)	Supplemental fluid	Gross power (MW)	N ₂ or CO ₂ parasitic load		Brine parasitic load		Net power (MW)		
			MW	% of gross	MW	% of gross	After total parasitic load	After N ₂ /CO ₂ parasitic load	Net power ratio*
5	N ₂	558.44	18.7	3.4	158.3	28.3	381.5	539.7	1.41
	CO ₂	495.47	2.1	0.4	115.8	23.8	377.6	493.4	1.31
4	N ₂	285.70	14.6	5.1	110.38	38.6	175.4	271.2	1.55
	CO ₂	273.43	2.0	0.7	86.6	31.7	184.9	271.5	1.49
3	N ₂	142.11	10.3	7.0	85.2	58.1	51.1	136.3	2.67
	CO ₂	121.76	1.4	1.11	61.8	50.2	62.8	124.6	1.99

Note: *Net power ratio is the net power after N₂/CO₂ parasitic load divided by the net power after total parasitic load.

For multi-fluid BES, we categorize dispatchable geothermal energy system operations into two time periods.

1. **Recharge period:** when the brine (and possibly N_2) parasitic load is entirely imposed. During this period, fluid/enthalpy production rate can also be reduced in order to achieve negative net power generation, which corresponds to taking (storing) energy from the electricity grid.
2. **Discharge period:** when only the minor (N_2 or CO_2) parasitic loads are imposed. During this period, net power is nearly equal to gross power and energy that was stored during the recharge period is returned to the electricity grid. The net power ratio (**Table 4.2**) is net power during the discharge period, divided by the constant (or average) net power that would occur with synchronous parasitic loading and constant fluid/enthalpy production.

The net power ratio increases with the brine parasitic load (**Table 4.2**), which is the parasitic load that is being time-shifted in the BES cases plotted in **Figure 4.3**. For these cases, net power ratio is a measure of how much the time-shifting of the brine parasitic load can increase net power when it is demanded by the electricity grid, compared to the conventional case of synchronous parasitic loading. **Figure 4.3** illustrates examples of diurnal BES where the time-shifted brine parasitic load ranges from 23.8 to 58.1 percent of gross power output, resulting in a net power ratio ranging from 1.31 to 2.67. The diurnal BES cycle consists of a 6-hour recharge period and an 18-hour discharge period. Two BES cases are shown: (1) BES case A, which time-shifts brine parasitic loading for a 6/18-hour recharge/discharge cycle and (2) BES case B, which is the same as case A, and reduces the fluid/enthalpy production rate by 50 percent during recharge. In all but one case (**Figure 4.3b**) BES case A yields a negative net power during recharge, corresponding to taking (storing) energy from the grid. When variable fluid/enthalpy production is added, all six cases yield negative net power during recharge. For the 3-km deep reservoir, the net power ratio is 2.67 and 1.99 for N_2 and CO_2 injection, respectively. When operated with synchronous parasitic loading and constant fluid/enthalpy production, the 3-km deep N_2 case generates a net power of 51.1 MW, whereas applying a 6/18-hour recharge/discharge cycle allows it to generate +136.3 and -204.4 MW during discharge and recharge, respectively. When fluid/enthalpy production is reduced by 50 percent during recharge, it generates +155.8 and -272.5 MW, during discharge and recharge, respectively. Clearly, the added benefit of multi-fluid BES has the potential of enhancing the financial viability of what would otherwise be considered a marginal geothermal resource, while simultaneously promoting implementation of other, intermittently available, renewable energy sources.

To provide a broader perspective on how diurnal BES operations might benefit a range of geothermal resources, including efficient, high-temperature resources, we consider a generic geothermal power plant with a net power output of 100 MW when operated with synchronous parasitic loading and constant fluid/enthalpy production. Parasitic loads of 10 to 60 percent and recharge/discharge periods of 6/18, 4/20, 3/21, and 2/22 hours are considered. **Table 4.3** shows the benefit of time-shifting the parasitic load, while **Table 4.4** adds to that the benefit of reducing fluid/enthalpy production by 50 percent during the recharge period. Even for efficient, high-temperature resources (e.g., 15 percent parasitic load), if the parasitic load can be imposed during a sufficiently compressed recharge window (e.g., two hours per day), a 100 MW power plant could deliver 117.6 MW to the grid during discharge and store -94.1 MW from the grid during recharge (**Table 4.3**). If for that same case, heat withdrawal from the reservoir and corresponding gross power output from the geothermal plant were reduced by 50 percent during the 2-hour recharge window, that plant could deliver 122.8 MW during discharge and store -159.6 MW during recharge (**Table 4.4**). The benefit of diurnal BES to both high- and low-temperature resources can be significant.

4.3 Future Work for Dispatchable Geothermal Energy Systems

This study provides first-order insights into the potential for multi-fluid geothermal energy systems to provide dispatchable renewable energy, based on simulations of generic, layered, laterally homogeneous reservoirs. Future work needs to consider the influence of permeability heterogeneity and reservoir compartmentalization, constrained by data from specific geologic settings. The geologic structure of real settings will provide some

lateral confinement, possibly obviating the need for the concentric well rings to surround the energy production and storage zone. The economics of multi-fluid geothermal well fields in real geologic structures should be assessed. Additional work is also needed to assess how the operations of current geothermal power systems can be modified to provide ancillary services and BES. Such work should analyze how geothermal power and energy storage systems can be engineered to respond to actual electrical-grid supply/demand histories. This work should include assessments of capital and operating costs in determining the financial viability of these systems.

Table 4.3. Net power for discharge and recharge periods when the parasitic load is time-shifted to occur during the listed recharge period. Gross power is held constant during the entire 24-hour diurnal BES cycle. When the geothermal power plant is operated with no BES, the net power output is 100 MW.

Recharge/discharge periods	Parasitic load	Net power (MW)						
		10%	15%	20%	30%	40%	50%	60%
6/18 hr	discharge	111.1	117.6	125.0	142.9	166.7	200.0	250.0
	recharge	66.7	47.1	25.0	-28.6	-100.0	-200.0	-350.0
4/20 hr	discharge	111.1	117.6	125.0	142.9	166.7	200.0	250.0
	recharge	44.4	11.8	-25.0	-114.3	-233.3	-400.0	-650.0
3/21 hr	discharge	111.1	117.6	125.0	142.9	166.7	200.0	250.0
	recharge	22.2	-23.5	-75.0	-200.0	-366.7	-600.0	-950.0
2/22 hr	discharge	111.1	117.6	125.0	142.9	166.7	200.0	250.0
	recharge	-22.2	-94.1	-175.0	-371.4	-633.3	-1000.0	-1550.0

Table 4.4. Net power for discharge and recharge periods when the listed parasitic load is time-shifted to occur during the listed recharge period. Gross power is reduced by 50 percent during recharge. When the geothermal power plant is operated with no BES, the net power output is 100 MW.

Recharge/discharge periods	Parasitic load	Net power (MW)						
		10%	15%	20%	30%	40%	50%	60%
6/18 hr	discharge	127.0	134.5	142.9	163.3	190.5	228.6	285.7
	recharge	12.7	-3.4	-42.9	-114.3	-209.5	-342.9	-543.9
4/20 hr	discharge	121.2	128.3	136.4	155.8	181.8	218.2	272.7
	recharge	-12.1	-51.3	-95.5	-202.6	-345.5	-545.5	-845.5
3/21 hr	discharge	118.5	125.5	133.3	152.4	177.8	213.3	266.7
	recharge	-35.6	-87.8	-146.7	-289.5	-444.4	-746.7	-1146.7
2/22 hr	discharge	115.9	122.8	130.4	149.1	173.9	208.7	260.9
	recharge	-81.2	-159.6	-247.8	-462.1	-747.8	-1147.8	-1747.8

5.0 Summary and Conclusions

State renewable portfolio standards are driving deep market penetration of intermittent wind and solar generation. This change in grid structure will substantially increase the uncertainty and variability in grid operations, and will increase the prices for ancillary services needed by operators to stabilize the grid. If ancillary service prices increase significantly above current levels for a sufficient number of hours during the year, geothermal power plant operators could capture additional revenues by operating plants in a flexible mode in order to provide these services. However, power purchase agreements reported in the recent press indicate that contracts are being configured to provide only energy sales. Energy prices under these contracts are significantly higher than current average ancillary service prices so there is insufficient incentive to reduce energy sales in order to provide ancillary services.

Energy storage in geothermal reservoirs provides another alternative source of revenues. Integrated operating strategies to provide energy arbitrage and ancillary services could provide enhanced revenue streams to

geothermal plant operators. Because bulk energy storage may be provided by time-shifting a portion of the parasitic load, the ability to store energy increases with the percentage of gross power that is parasitic load capable of being time-shifted. Thus, less-efficient, low-temperature resources can store more energy, relative to gross power output, than more-efficient, high-temperature resources. Because the relative benefit of energy storage can be quite large for low-temperature resources, this may enable financial viability of what would otherwise be considered an uneconomic geothermal resource, while promoting implementation of other, intermittently available, renewable energy sources. Moreover, high-temperature resources can also be used to store energy if the *recharge* window during which the parasitic load is imposed is sufficiently compressed (e.g., two hours per day) and if gross power is cut back during the recharge window. Finally, all geothermal resources have the potential of providing ancillary services by using a combination of modulating the magnitude and timing of the parasitic load and varying gross power.

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Appendix A: Energy and Ancillary Service Price Patterns

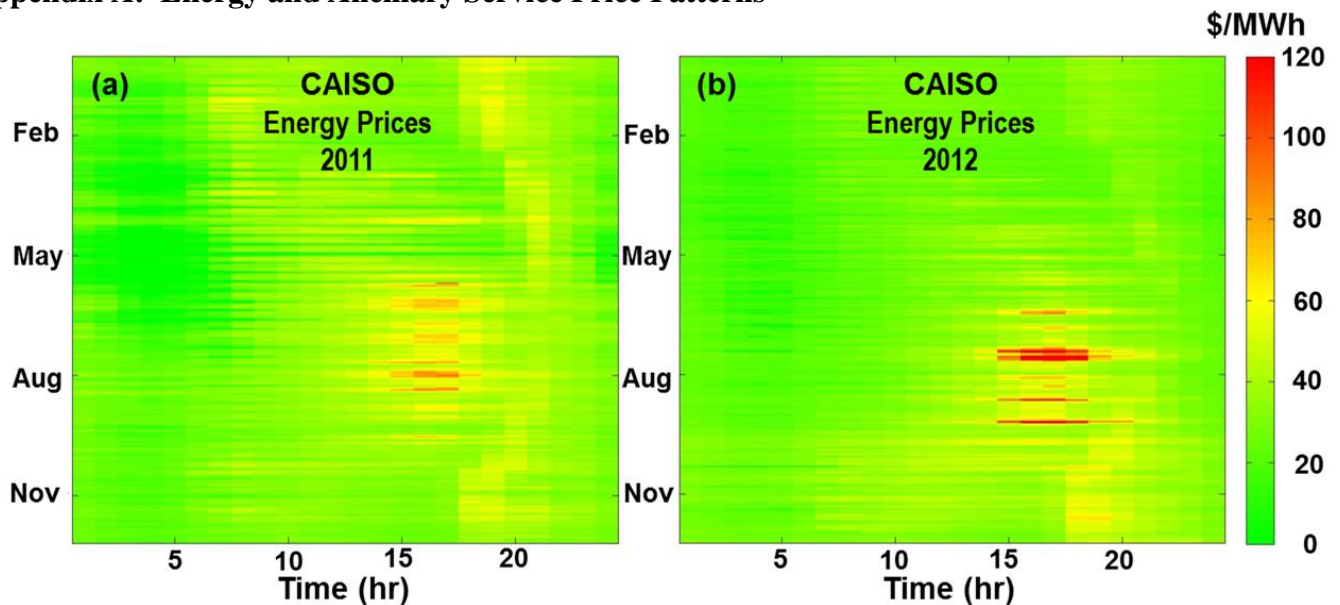


Figure A.1. CAISO energy prices (\$/MWh) are plotted for (a) 2011 and (b) 2012.

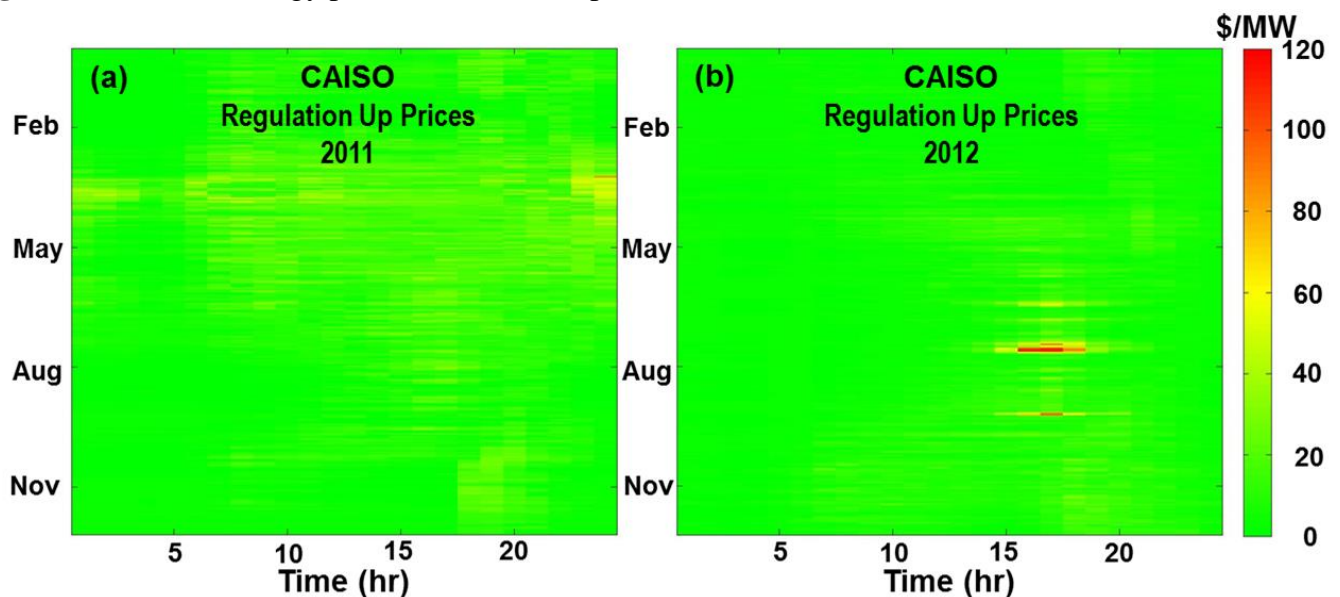
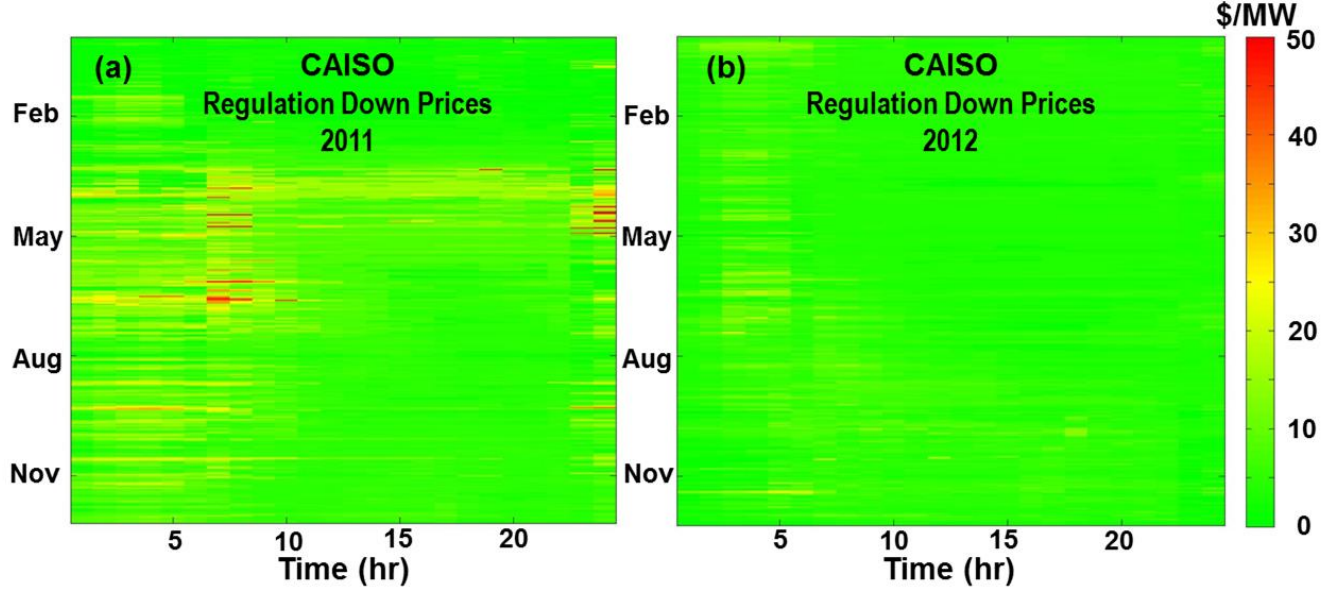
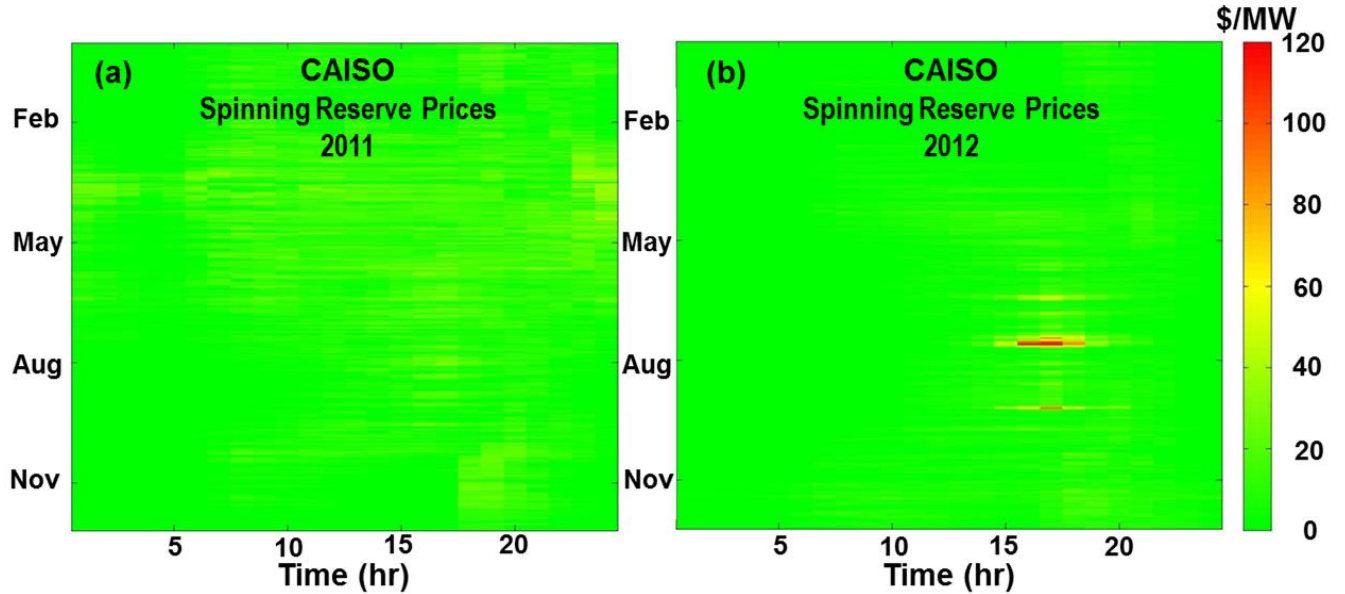


Figure A.2. CAISO ancillary service regulation-up prices (\$/MW) are plotted for (a) 2011 and (b) 2012.**Figure A.3.** CAISO ancillary service regulation-down prices (\$/MW) are plotted for (a) 2011 and (b) 2012. Note that the color scale is different from the other figures in **Appendix A**.**Figure A.4.** CAISO ancillary service spinning reserve prices (\$/MW) are plotted for (a) 2011 and (b) 2012.

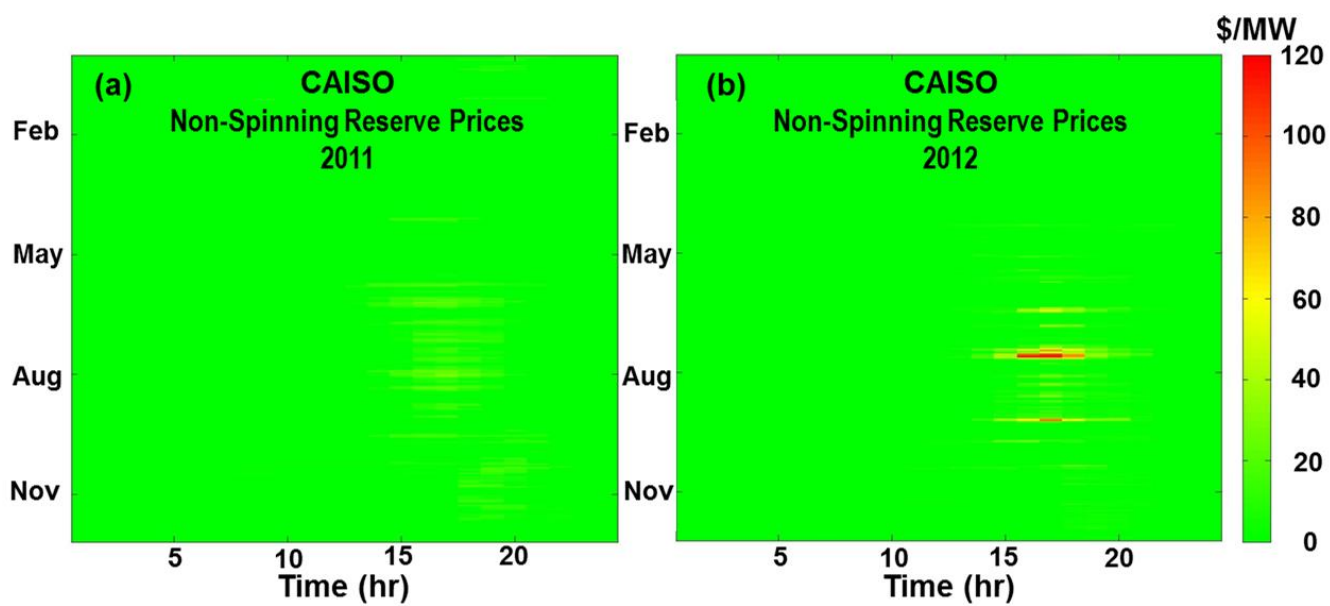


Figure A.5. CAISO ancillary service non-spinning reserve prices (\$/MW) are plotted for (a) 2011 and (b) 2012.